Preprint typeset in JHEP style - HYPER VERSION

TU-897

Light Higgsino in Heavy Gravitino Scenario with Successful Electroweak Symmetry Breaking

Kwang Sik Jeong, Masatoshi Shimosuka,[*] Masahiro Yamaguchi

Department of Physics, Tohoku University, Sendai 980-8578, Japan
E-mail : ksjeong@tuhep.phys.tohoku.ac.jp, shimosuka@tuhep.phys.tohoku.ac.jp, yama@tuhep.phys.tohoku.ac.jp

Abstract: We consider, in the context of the minimal supersymmetric standard model, the case where the gravitino weighs 10^6 GeV or more, which is preferred by various cosmological difficulties associated with unstable gravitinos. Despite the large Higgs mixing parameter B together with the little hierarchy to other soft supersymmetry breaking masses, a light higgsino with an electroweak scale mass leads to successful electroweak symmetry breaking, at the price of fine-tuning the higgsino mixing μ parameter. Furthermore the light higgsinos produced at the decays of gravitinos can constitute the dark matter of the universe. The heavy squark mass spectrum of $O(10^4)$ GeV can increase the Higgs boson mass to about 125 GeV or higher.

Keywords: Supersymmetry breaking, Supersymmetric Standard Model.

[*]Current address: Ministry of Education, Culture, Sports, Science and Technology (MEXT), Tokyo 100-8959, Japan

Contents

1. Introduction

Although supersymmetry (SUSY) [1, 2] is a promising candidate for physics beyond the standard model (SM), a closer look reveals its weak spots. Among other things, the gravitino with the very long lifetime is known to be a potentially dangerous existence in cosmology [3, 4].

The abundance of the unstable gravitinos is severely constrained by the success of the big-bang nucleosynthesis for its mass up to $\sim 5 \times 10^4$ GeV [5, 6, 7]. Even for a heavier gravitino, cosmology is not yet free from the fear of the gravitino decay. When the gravitinos were amply produced at the decay of the moduli [8, 9, 10] (see also ref. [11] for an earlier discussion) or other scalar fields [12, 13, 14], or in the thermal bath with high reheat temperature, the lightest superparticles (LSPs) produced by the gravitino decays would exceed the observed abundance of the dark matter of the universe. Given a neutralino LSP with mass around 100 GeV, the gravitino should weigh 10^6 GeV or even more [9]. To solve this problem, a previous work postulated the existence of a lighter LSP in an extension of the minimal supersymmetric standard model (MSSM) [15].

In this paper, we shall revisit this problem within the framework of the MSSM. The gravitino mass is generically related to soft SUSY breaking masses. This is because the vacuum expectation value of the chiral compensator auxiliary field F_ϕ is comparable to the gravitino mass $m_{3/2}$ in size unless one considers a very specific SUSY breaking scenario. In this case, the SUSY-breaking Higgs mixing parameter B is comparable to F_ϕ, and thus to $m_{3/2}$. Furthermore, we assume that the contribution from the anomaly mediation to other soft masses is inevitable and is not cancelled by other SUSY breaking mediation contributions. Thus the soft masses should satisfy

$$m_{\rm soft} \gtrsim \frac{1}{8\pi^2} m_{3/2}. \tag{1.1}$$

On the other hand, the supersymmetric higgsino mass parameter μ is not constrained by this argument. We are thus led to consider the case where the higgsino is light with the hierarchical mass spectrum[1]:

$$\mu \sim \mathcal{O}(100)\ \mathrm{GeV} \ll m_{\mathrm{soft}} \sim \mathcal{O}(10^4)\ \mathrm{GeV} \ll m_{3/2} \sim \mathcal{O}(10^6)\ \mathrm{GeV}. \tag{1.2}$$

We note that the suppressed soft masses compared to the gravitino mass are realized in the KKLT setup [16]. In this case, the resulting soft masses are of the mixed modulus-anomaly mediation [17, 18, 19, 20, 21]. Our argument given here can apply to a wider class of models and thus we do not specify a particular mediation mechanism.

As we will show shortly, the electroweak symmetry breaking (EWSB) successfully takes place with this hierarchy. Furthermore the higgsino LSP abundance produced by the gravitino decays is consistent with the measured value of the dark matter abundance and hence can constitute the dark matter of the universe.

The Higgs sector in this scenario contains a SM-like Higgs boson whereas all others become very heavy $\sim O(10^4)$ GeV. We will show that the SM-like Higgs boson naturally has mass in the range suggested by the recent data from ATLAS and CMS at the Large Hadron Collider (LHC) [22].

2. Electroweak Symmetry Breaking

Let us begin by investigating how the EWSB takes place with the mass spectrum eq. (1.2). The neutral part of the tree-level Higgs potential in the MSSM is given by

$$\begin{aligned} V =& (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (B\mu H_u^0 H_d^0 + c.c.) \\ &+ \frac{1}{8}(g_1^2 + g_2^2)(|H_u^0|^2 - |H_d^0|^2)^2, \end{aligned} \tag{2.1}$$

where $m_{H_u}^2$ and $m_{H_d}^2$ are SUSY breaking mass squared parameters for hypercharge 1/2 and $-1/2$ Higgs doublet, respectively, and g_1, g_2 are $U(1)_Y, SU(2)_L$ coupling constants.

It is well known that the following two conditions should be satisfied in order that the theory exhibits the EWSB:

1. The scalar potential is stable along the D-flat direction, $|H_u^0|^2 = |H_d^0|^2$, where the quartic terms are absent. This yields

$$2|B\mu| < 2|\mu|^2 + m_{H_d}^2 + m_{H_u}^2. \tag{2.2}$$

2. One of the eigenvalues of the squared-mass matrix is negative, and so is the determinant

$$(|\mu|^2 + m_{H_d}^2)(|\mu|^2 + m_{H_u}^2) - |B\mu|^2 < 0. \tag{2.3}$$

[1] Another possibility one can consider is that a relatively heavy neutralino will annihilate very effectively via Higgs resonance to reduce its relic abundance. However, we will discard this case as it requires fine turning of the masses of the neutralino and the Higgs boson.

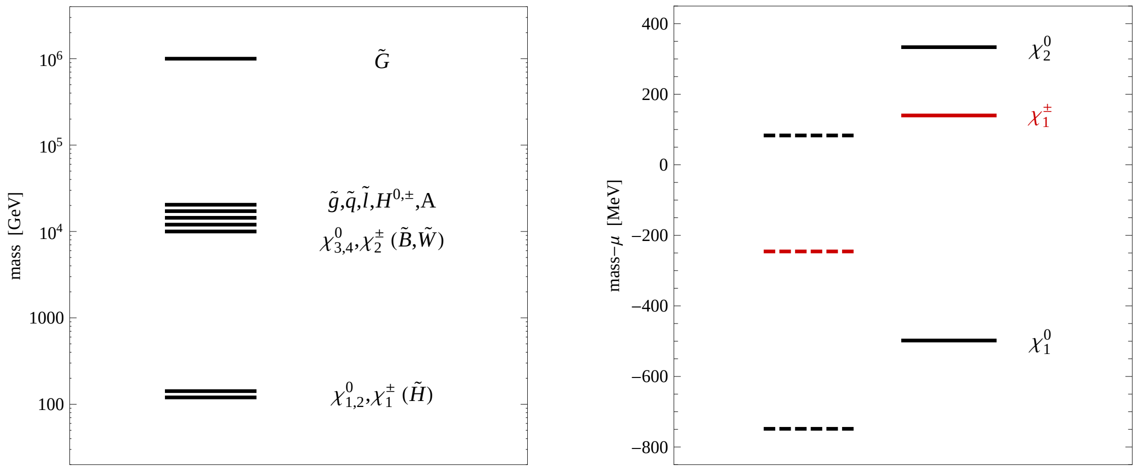

Figure 1: The mass spectrum in heavy gravitino scenario with a light higgsino. The right plot shows the masses of $\chi^0_{1,2}$ and $\chi^\pm_1$ for $\tan\beta = 2$ (dashed lines) and $\tan\beta = 10$ (solid lines) in the case with $\mu = 120\,\text{GeV}$ and $M_1 = M_2 = 10^4\,\text{GeV}$.

To realize the electroweak scale from the much larger soft masses, the negative eigenvalue should be tuned to be at the electroweak scale. Then the magnitude of the determinant becomes much smaller than the typical soft mass scale, which implies $|B\mu|^2 \sim m^2_{H_u} m^2_{H_d}$ for $\mu \ll m_{\rm soft}$. The EWSB thus requires both $m^2_{H_u}$ and $m^2_{H_d}$ to be positive, and is driven by a large $B\mu$ term. To be more precise, the extremum conditions of the Higgs potential read

$$
\begin{aligned}
m^2_{H_u} &\simeq \frac{m^2_{H_d}}{\tan^2\beta}, \\
|\mu| &\simeq \frac{m^2_{H_d}}{|B|\tan\beta},
\end{aligned}
\tag{2.4}
$$

for $1 \ll \tan^2\beta \ll m^2_{H_d}/|\mu|^2$ where $\tan\beta = \langle|H^0_u|\rangle/\langle|H^0_d|\rangle$. It is interesting to observe that

$$
\mu \sim \frac{1}{(8\pi^2)^2} m_{3/2}, \tag{2.5}
$$

when $B \sim m_{3/2}$ and $\sqrt{m_{H_u} m_{H_d}} \sim m_{3/2}/8\pi^2$, which is anticipated from the anomaly mediation contribution. For $m_{3/2} \sim 10^6$ GeV, one naturally obtains $\mu \sim 100$ GeV. A rather small m_{H_u} ($\sim m_{H_d}/\tan\beta$) at a low energy scale would be the result of a negative radiative correction associated with the top Yukawa coupling.

In fig. 1, we illustrate the superparticle mass spectrum in heavy gravitino scenario. Since $\mu \ll m_{\rm soft}$, the lightest chargino and the two lightest neutralinos are dominated by the higgsino components and closely degenerate in masses.

3. Higgs Boson Mass

Below the scale $m_{\rm soft} \sim 10^4\,\text{GeV}$, one combination of H_u and H_d behaves like the SM Higgs

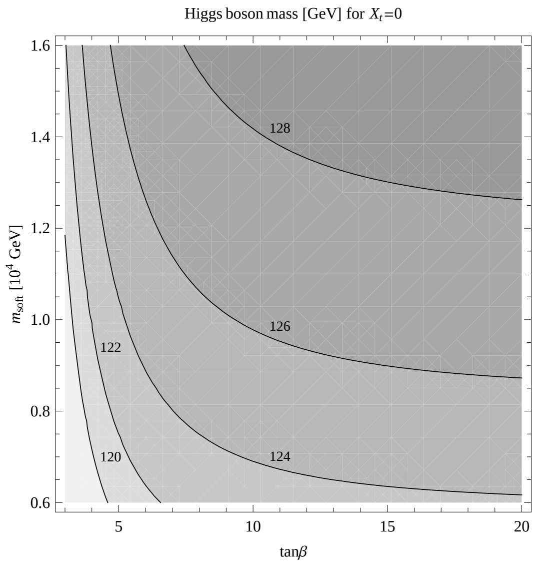

Figure 2: The contours for the Higgs boson mass in the $\tan\beta$-$m_{\rm soft}$ plane for heavy gravitino scenario with $\mu = 120\,\text{GeV}$. The stop mixing X_t is set to zero.

doublet scalar while sfermions, gauginos and other heavy Higgs bosons decouple from the theory. In the low energy effective theory, the mass of the SM-like Higgs boson h can be estimated from the relation $m_h^2 = \lambda(m_h)v^2$ where $\lambda(m_h)$ is the Higgs quartic coupling renormalized at m_h, and v is the vacuum expectation value of the SM-like Higgs scalar. The Higgs coupling λ at $m_{\rm soft}$ is given by

$$\lambda(m_{\rm soft}) = \frac{g_1^2 + g_2^2}{4}\cos^2 2\beta + \frac{3y_t^4}{8\pi^2}\left(X_t^2 - \frac{X_t^4}{12}\right), \tag{3.1}$$

and its low energy value is determined by the renormalization group equations, which are affected by the higgsinos with mass $\mu \sim 10^2$ GeV. Here y_t is the top Yukawa coupling, and $X_t = (A_t - \mu\cot\beta)/m_{\rm soft}$ is the stop mixing parameter.

The Higgs quartic coupling $\lambda(m_h)$ gets a large positive contribution from the loops involving the top Yukawa coupling [23, 24, 25]. For heavy stops with mass $\sim 10^4$ GeV, this loop contribution makes the Higgs boson have a mass around 125 GeV, which lies in the range where the LHC experiments reported an excess of Higgs-like events over the background expectation [22]. A stop mixing due to the trilinear A-term can raise the Higgs mass further.

Fig. 2 shows the Higgs boson mass for $\mu = 120$ GeV without the stop mixing $X_t = 0$. One can see that m_h is around 125GeV for $m_{\rm soft} = 10^4$GeV. The Higgs mass has a negligible dependence on μ since the higgsinos only contribute to the beta function coefficients for $g_{1,2}$. For instance, if the higgsinos decouple with mass $\mu \sim m_{\rm soft}$, m_h increases slightly by about 0.1% compared to the case with $\mu = 120$ GeV.

4. Higgsino Relic Abundance

Let us next see whether the neutral higgsino is the LSP in the mass spectrum eq. (1.2). We define the mass difference Δm between the lightest chargino χ_1^+ and the lightest neutralino χ_1^0 as

$$\begin{aligned}\Delta m &\equiv m_{\chi_1^+} - m_{\chi_1^0} \\ &= \Delta m^{(0)} + \Delta m^{(1)}_{\text{gauge}} + \Delta m^{(1)}_{\text{Yukawa}},\end{aligned} \tag{4.1}$$

where $\Delta m^{(1)}$ is the 1-loop correction to the tree-level mass difference $\Delta m^{(0)}$. In the limit of $m_Z, |\mu| \ll M_1, M_2$ where m_Z is the Z boson mass and M_1, M_2 are $U(1)_Y$ and $SU(2)_L$ gaugino masses, the lightest chargino and neutralino consist mainly of the charged and neutral higgsino, respectively. Taking a rather unusual convention that μ is positive while M_1, M_2 have either sign, we find the two neutral higgsinos $\widetilde{H}_S, \widetilde{H}_A$ have masses

$$\begin{aligned}M_{\widetilde{H}_S} &= \mu + \frac{1-\sin 2\beta}{2} m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right), \\ M_{\widetilde{H}_A} &= \mu - \frac{1+\sin 2\beta}{2} m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right),\end{aligned} \tag{4.2}$$

where θ_W is the Weinberg angle. The charged higgsino has mass

$$M_{\widetilde{H}^\pm} = \mu - \frac{m_W^2 \sin 2\beta}{M_2}, \tag{4.3}$$

where m_W is the W boson mass. Thus, the tree-level mass difference is

$$\Delta m^{(0)} = M_{\widetilde{H}^\pm} - \min\left(M_{\widetilde{H}_S}, M_{\widetilde{H}_A} \right). \tag{4.4}$$

We find that when M_1 and M_2 have the same sign, $\Delta m^{(0)}$ is always positive. But more generally, $\Delta m^{(0)}$ can take either sign. The magnitude of $\Delta m^{(0)}$ is typically

$$\left| \Delta m^{(0)} \right| \simeq 0.3\text{ GeV} \times \left(\frac{|M_2|}{10^4\text{ GeV}} \right)^{-1} \left| 1 + \frac{M_2}{M_1} \tan^2\theta_W \right| \tag{4.5}$$

for $\tan\beta \gg 1$. Furthermore, the 1-loop correction from gauge boson loops

$$\begin{aligned}\Delta m^{(1)}_{\text{gauge}} &= \frac{g_2^2 \sin^2\theta_W}{8\pi^2} |\mu| \int_0^1 dx (x+1) \ln\left(1 + \frac{1-x}{x^2} \frac{m_Z^2}{\mu^2} \right) \\ &= 0.24\text{ GeV} \to 0.35\text{ GeV} \quad (\text{for } |\mu| = 100\text{ GeV} \to \infty)\end{aligned} \tag{4.6}$$

is always positive, whereas that from the top-stop loops is estimated as

$$\Delta m^{(1)}_{\text{top-stop}} \sim -0.027\text{ GeV} \times \left(\frac{m_t}{170\text{ GeV}} \right)^4 \left(\frac{m_{\tilde{t}}}{10^4\text{ GeV}} \right)^{-2} \frac{A_t}{10^4\text{ GeV}} \frac{1}{\sin^2\beta}, \tag{4.7}$$

where m_t is the top mass, $m_{\tilde{t}}$ is the stop mass scale, and A_t is the mass scale included in the trilinear scalar term [26]. We represent the top-stop loop contribution explicitly

because it is the largest contribution in the Yukawa one. As we can see in eq. (4.7), the Yukawa contributions to the mass difference are negligibly small compared to the gauge boson contribution. Thus, we find

$$\Delta m > 0 \tag{4.8}$$

in the sizable region of the parameter space.

Now we will discuss the relic abundance of the neutral higgsino LSP. The LSPs are produced by the decays of gravitinos followed by the pair-annihilation among them. The abundance highly depends on the thermal averaged annihilation cross section of the LSPs. Here only the W boson or Z boson pairs are taken account of in the final state because other annihilation processes are highly suppressed due to the heavy soft masses. Thus the cross section is computed to be [27]

$$\langle \sigma_{\rm ann} v_{\rm rel} \rangle = \frac{g^4}{32\pi} \frac{1}{m_{\chi_1^0}^2} \left[\frac{(1-x_W)^{3/2}}{(2-x_W)^2} + \frac{1}{2\cos^4\theta_W} \frac{(1-x_Z)^{3/2}}{(2-x_Z)^2} \right], \tag{4.9}$$

where $m_{\chi_1^0} \simeq |\mu|$, $x_W = m_W^2/m_{\chi_1^0}^2$ and $x_Z = m_Z^2/m_{\chi_1^0}^2$.

In computing the annihilation cross section, the Boltzmann distribution was, for simplicity, assumed for the higgsino momentum distribution, whose justification may be quite non-trivial [28]. We note, however, this simplification does not cause any significant change to our result as far as the higgsinos are non-relativistic and the annihilation occurs in the unsuppressed S-wave. Also, we ignored the possible coannihilation effects [29], which do not bring any dramatic alternation of our result.

As the nature of the R-odd particles, the gravitino decay yields (at least) one LSP production under the R-parity conservation. Thus in the absence of the annihilation among the LSPs, the final yield of the LSPs would be the same as the initial yield of the gravitinos. When the gravitino abundance is large enough, which we assume to be the case, the annihilation among the LSPs becomes effective. We note that the gravitino decay width is given by

$$\Gamma_{3/2} = \frac{193}{384\pi} \frac{m_{3/2}^3}{M_{Pl}^2}, \tag{4.10}$$

corresponding to the temperature at the gravitino decay

$$\begin{aligned} T_{3/2} &\simeq \left(\frac{90}{\pi^2 g_*(T_{3/2})} \right)^{1/4} \sqrt{\Gamma_{3/2} M_{Pl}} \\ &\simeq 0.25\text{GeV} \times \left(\frac{g_*(T_{3/2})}{10} \right)^{-1/4} \left(\frac{m_{3/2}}{10^6\text{GeV}} \right)^{3/2}, \end{aligned} \tag{4.11}$$

where the effective number of relativistic degrees of freedom g_* changes from about 100 to 10 by the QCD phase transition at around 0.2 GeV. Thus, the LSPs are produced after the freeze-out of the LSPs from the thermal bath takes place (with the temperature $T_f \simeq m_{\chi_1^0}/25 - m_{\chi_1^0}/20$). In this case, one can estimate the yield of the LSPs as [30]:

$$\left.\frac{n_{\chi^0}}{s}\right|_{T_{3/2}} \simeq \left.\frac{H(T)}{\langle \sigma_{\rm ann} v_{\rm rel} \rangle s}\right|_{T_{3/2}} = \frac{1}{4} \left(\frac{90}{\pi^2 g_*(T_{3/2})} \right)^{1/2} \frac{1}{\langle \sigma_{\rm ann} v_{\rm rel} \rangle T_{3/2} M_{Pl}}. \tag{4.12}$$

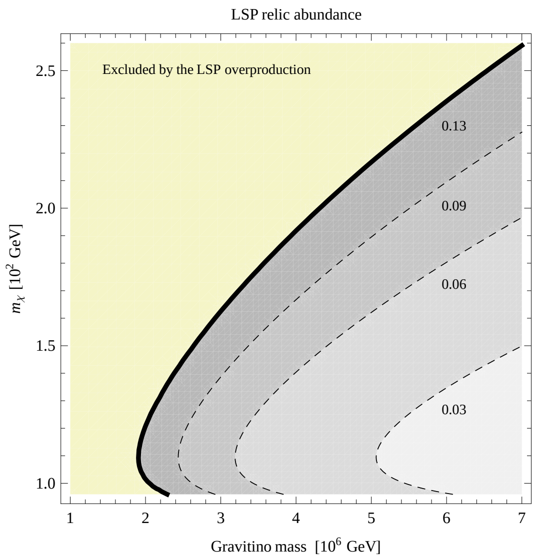

Figure 3: The constant contours for the density parameter $\Omega_{\chi_1^0} h^2$ are shown in the $m_{\chi_1^0}$-$m_{3/2}$ plane. Tree dashed lines represent the contours of $\Omega_{\chi_1^0} h^2 = 0.03, 0.06, 0.09$, from the above respectively. The real one stands for $\Omega_{\chi_1^0} h^2 = 0.13$ that is the 95 % C.L. upper bound of the LSP abundance restricted by the dark matter observation.

From eq. (4.9) and eq. (4.12), the ratio of the LSP mass density to the entropy density is straightforwardly given by

$$\begin{aligned}\frac{\rho_{\chi_1^0}}{s} &\simeq 0.22 \times 10^{-9}\,\mathrm{GeV} \\ &\quad\times \left[\frac{1}{2\cos^4\theta_W}\frac{(1-x_Z)^{3/2}}{(2-x_Z)^2} + \frac{(1-x_W)^{3/2}}{(2-x_W)^2}\right]^{-1} \left(\frac{m_{\chi_1^0}}{100\mathrm{GeV}}\right)^3 \\ &\quad\times \left(\frac{g_*(T_{3/2})}{10}\right)^{-1/4} \left(\frac{m_{3/2}}{10^6\mathrm{GeV}}\right)^{-3/2}, \qquad (4.13)\end{aligned}$$

which corresponds to the density parameter

$$\begin{aligned}\Omega_{\chi_1^0} h^2 \simeq 0.060 \times &\left[\frac{1}{2\cos^4\theta_W}\frac{(1-x_Z)^{3/2}}{(2-x_Z)^2} + \frac{(1-x_W)^{3/2}}{(2-x_W)^2}\right]^{-1} \left(\frac{m_{\chi_1^0}}{100\mathrm{GeV}}\right)^3 \\ &\times \left(\frac{g_*(T_{3/2})}{10}\right)^{-1/4} \left(\frac{m_{3/2}}{10^6\mathrm{GeV}}\right)^{-3/2}, \qquad (4.14)\end{aligned}$$

where $h \simeq 0.72$ is the Hubble constant in unit of 100 km/s/Mpc.

In fig. 3, we draw constant contours for the density parameter $\Omega_{\chi_1^0} h^2$ in the $m_{\chi_1^0}$-$m_{3/2}$ plane. The real line shows $\Omega_{\chi_1^0} h^2 = 0.13$ that is the 95 % C.L. upper bound of the LSP abundance restricted by the dark matter observation [31]. Remarkably, there is no LSP overproduction problem in the mass spectrum eq. (1.2) and we can conclude the neutral higgsino constitutes the dark matter of the universe.

5. Discussion and Summary

Since $\chi_{1,2}^0$ and χ_1^+ are all higgsino-like for $\mu \ll m_{\rm soft}$, only the interactions $Z\chi_1^0\chi_2^0$, $W^-\chi_1^+\chi_{1,2}^0$, $\gamma\chi_1^+\chi_1^-$ and $Z\chi_1^+\chi_1^-$ have non-negligible couplings. Heavy gravitino scenario with the mass spectrum eq. (1.2) generally leads to $m_\pi < \Delta m \lesssim 1\,{\rm GeV}$ with m_π being the pion mass, for which the lightest chargino decay is dominated by the single pion mode $\chi_1^+ \to \chi_1^0\pi^+$:

$$\Gamma_{\chi_1^+\to\chi_1^0\pi^+} = \frac{G_F^2}{\pi}\cos^2\theta_C f_\pi^2 \Delta m^3 \left(1-\frac{m_\pi^2}{\Delta m^2}\right)^{1/2}$$
$$\simeq \frac{1}{0.2{\rm cm}}\left(\frac{\Delta m}{500{\rm MeV}}\right)^3\left(1-\frac{m_\pi^2}{\Delta m^2}\right)^{1/2}, \tag{5.1}$$

where f_π is the pion decay constant, and θ_C is the Cabbibo angle. Thus, it would be difficult for the lightest chargino to produce a visible track in the detector unless it is highly boosted.[2] Also, produced pions would be too soft to be detected. The mass difference between the two lightest neutralinos is similar to Δm in size, and thus the detection of the decay products of χ_2^0 would be challenging as well. On the other hand, at e^+e^- colliders, the processes $e^+e^- \to \gamma\chi_1^0\chi_2^0$, $\gamma\chi_1^+\chi_1^-$ mediated by virtual Z exchange become important, and would provide a visible signal if a hard photon radiation occurs in the initial state.

The direct detection of dark matter is also challenging because the couplings $h\chi_1^0\chi_1^0$ and $Z\chi_1^0\chi_1^0$ are suppressed by a small factor $m_W/M_{1,2}$ for a higgsino-like χ_1^0. The spin-dependent cross section with proton due to the $Z\chi_1^0\chi_1^0$ coupling is approximately given by [38]

$$\sigma_{\rm SD} \sim 0.8\times10^{-42}{\rm cm}^2 \times \left(\frac{M_2}{10^4{\rm GeV}}\right)^{-2}\left(\frac{\mu}{100{\rm GeV}}\right)^{-2}\cos^2 2\beta, \tag{5.2}$$

for $M_1 = M_2$. The spin-independent scattering is mediated mainly by Higgs boson exchange, and has a cross section smaller than $\sigma_{\rm SD}$ by about 5 orders of magnitude. Thus, in both cases, the scattering is too small to be detectable by current experiments. On the other hand, the higgsino annihilation into $\gamma\gamma$ and γZ can provide an interesting signal for the indirect detection of dark matter. Dark matter is detectable by observing a γ-ray line with energy $E_\gamma = m_{\chi_1^0}$ or $m_{\chi_1^0} - m_Z^2/4m_{\chi_1^0}$ coming from the Galatic center. The cross section for $\chi_1^0\chi_1^0 \to \gamma\gamma$ is $\sigma v \approx 10^{-28}{\rm cm}^3/{\rm s}$ for the higgsino LSP, and the annihilation into γZ has a little bit larger cross section [39, 40]. The annihilation cross sections are about one order of magnitude below the experimental upper limits [41]. Future experiments would be possible to observe γ-ray lines from the processes $\chi_1^0\chi_1^0 \to \gamma\gamma, \gamma Z$, providing a signature of dark matter.

Though we have focused on the case with $\mu \ll m_{\rm soft} \sim m_{3/2}/8\pi^2$, it would be possible to have a light gaugino with mass $\ll m_{3/2}/8\pi^2$ if the anomaly mediation contribution is cancelled by some other contribution. Then mass differences among the light charginos and neutralinos become larger as long as the higgsino remains the dominant component of χ_1^0. This increases the detection potential of SUSY at the LHC as the decay of chargino can

[2] See refs. [32, 33, 34, 35, 36, 37] for discussions of collider searches.

produce hard enough leptons or jets. In addition, because the couplings $h\chi_1^0\chi_1^0$ and $Z\chi_1^0\chi_1^0$ are enhanced, there are more possibilities also for the direct detection of dark matter.

To conclude, we have shown that the heavy gravitino scenario with the hierarchical mass spectrum

$$\mu \sim 10^2 \text{ GeV} \ll m_{\text{soft}} \sim 10^4 \text{ GeV} \ll m_{3/2} \sim 10^6 \text{ GeV} \tag{5.3}$$

can explain well the EWSB while solving the cosmological problems associated with the gravitino. The EWSB is achieved at the correct scale for $B \sim m_{3/2} \sim 8\pi^2 m_{\text{soft}}$, as is generally the case when the anomaly mediation is a main source of superparticle masses. Furthermore, the higgsino LSP abundance produced by the gravitino decays is consistent with the observed value. We also note that the heavy stop with mass $m_{\text{soft}} \sim 10^4$ GeV yields the SM-like Higgs boson mass around 125 GeV without invoking a large stop mixing.

Acknowledgments

We would like to thank Ryuichiro Kitano for useful discussion. This work was supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture (MEXT), Japan, No. 23104008 and No. 23540283.

References

[1] H. P. Nilles, "Supersymmetry, Supergravity And Particle Physics," Phys. Rept. **110**, 1 (1984).

[2] H. E. Haber and G. L. Kane, "The Search For Supersymmetry: Probing Physics Beyond The Standard Model," Phys. Rept. **117**, 75 (1985).

[3] M. Y. Khlopov and A. D. Linde, "Is It Easy To Save The Gravitino?," Phys. Lett. B **138** (1984) 265; J. R. Ellis, J. E. Kim and D. V. Nanopoulos, "Cosmological Gravitino Regeneration And Decay," Phys. Lett. B **145**, 181 (1984); R. Juszkiewicz, J. Silk and A. Stebbins, "Constraints On Cosmologically Regenerated Gravitinos," Phys. Lett. B **158** (1985) 463; J. R. Ellis, D. V. Nanopoulos and S. Sarkar, "The Cosmology Of Decaying Gravitinos," Nucl. Phys. B **259**, 175 (1985); D. Lindley, "Hadronic Decays Of Cosmological Gravitinos," Phys. Lett. B **171**, 235 (1986).

[4] M. Kawasaki and T. Moroi, "Gravitino production in the inflationary universe and the effects on big bang nucleosynthesis," Prog. Theor. Phys. **93**, 879 (1995) [arXiv:hep-ph/9403364]; "Electromagnetic Cascade In The Early Universe And Its Application To The Big Bang Nucleosynthesis," Astrophys. J. **452**, 506 (1995) [arXiv:astro-ph/9412055]; E. Holtmann, M. Kawasaki, K. Kohri and T. Moroi, "Radiative decay of a long-lived particle and big-bang nucleosynthesis," Phys. Rev. D **60**, 023506 (1999) [arXiv:hep-ph/9805405].

[5] M. Kawasaki, K. Kohri and T. Moroi, "Hadronic decay of late-decaying particles and big-bang nucleosynthesis," Phys. Lett. B **625**, 7 (2005) [arXiv:astro-ph/0402490]; "Big-bang nucleosynthesis and hadronic decay of long-lived massive particles," Phys. Rev. D **71**, 083502 (2005) [arXiv:astro-ph/0408426].

[6] K. Kohri, T. Moroi and A. Yotsuyanagi, "Big-bang nucleosynthesis with unstable gravitino and upper bound on the reheating temperature," Phys. Rev. D **73**, 123511 (2006) [arXiv:hep-ph/0507245].

[7] K. Kohri, M. Yamaguchi and J. Yokoyama, "Neutralino dark matter from heavy gravitino decay," Phys. Rev. D **72**, 083510 (2005) [arXiv:hep-ph/0502211].

[8] M. Endo, K. Hamaguchi and F. Takahashi, "Moduli-induced gravitino problem," Phys. Rev. Lett. **96**, 211301 (2006) [arXiv:hep-ph/0602061].

[9] S. Nakamura and M. Yamaguchi, "Gravitino production from heavy moduli decay and cosmological moduli problem revived," Phys. Lett. B **638**, 389 (2006) [arXiv:hep-ph/0602081].

[10] M. Dine, R. Kitano, A. Morisse and Y. Shirman, "Moduli decays and gravitinos," Phys. Rev. D **73**, 123518 (2006) [arXiv:hep-ph/0604140].

[11] I. Joichi and M. Yamaguchi, "Heavy Polonyi field as a solution of the Polonyi problem," Phys. Lett. B **342**, 111 (1995) [arXiv:hep-ph/9409266].

[12] M. Endo, F. Takahashi and T. T. Yanagida, "Anomaly-induced inflaton decay and gravitino-overproduction problem," Phys. Lett. B **658**, 236 (2008) [hep-ph/0701042].

[13] M. Endo, F. Takahashi and T. T. Yanagida, "Inflaton Decay in Supergravity," Phys. Rev. D **76**, 083509 (2007) [arXiv:0706.0986 [hep-ph]].

[14] T. Asaka, S. Nakamura and M. Yamaguchi, "Gravitinos from heavy scalar decay," Phys. Rev. D **74**, 023520 (2006) [hep-ph/0604132].

[15] S. Nakamura, K. i. Okumura and M. Yamaguchi, "Axionic Mirage Mediation," Phys. Rev. D **77**, 115027 (2008) [arXiv:0803.3725 [hep-ph]].

[16] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, "De Sitter vacua in string theory," Phys. Rev. D **68**, 046005 (2003) [arXiv:hep-th/0301240].

[17] K. Choi, A. Falkowski, H. P. Nilles, M. Olechowski and S. Pokorski, "Stability of flux compactifications and the pattern of supersymmetry breaking," JHEP **0411**, 076 (2004) [hep-th/0411066].

[18] K. Choi, A. Falkowski, H. P. Nilles and M. Olechowski, "Soft supersymmetry breaking in KKLT flux compactification," Nucl. Phys. B **718**, 113 (2005) [hep-th/0503216].

[19] M. Endo, M. Yamaguchi and K. Yoshioka, "A Bottom-up approach to moduli dynamics in heavy gravitino scenario: Superpotential, soft terms and sparticle mass spectrum," Phys. Rev. D **72**, 015004 (2005) [hep-ph/0504036].

[20] K. Choi, K. S. Jeong and K. -i. Okumura, "Phenomenology of mixed modulus-anomaly mediation in fluxed string compactifications and brane models," JHEP **0509**, 039 (2005) [hep-ph/0504037].

[21] A. Falkowski, O. Lebedev and Y. Mambrini, "SUSY phenomenology of KKLT flux compactifications," JHEP **0511**, 034 (2005) [hep-ph/0507110].

[22] The ATLAS and CMS collaborations, ATLAS-CONF-2011-163 and CMS-PAS-HIG-11-032 (December, 2011).

[23] Y. Okada, M. Yamaguchi and T. Yanagida, "Upper bound of the lightest Higgs boson mass in the minimal supersymmetric standard model," Prog. Theor. Phys. **85**, 1 (1991); "Renormalization Group Analysis On The Higgs Mass In The Softly Broken Supersymmetric Standard Model," Phys. Lett. B **262**, 54 (1991).

[24] J. R. Ellis, G. Ridolfi and F. Zwirner, "Radiative corrections to the masses of supersymmetric Higgs bosons," Phys. Lett. B **257**, 83 (1991).

[25] H. E. Haber and R. Hempfling, "Can the mass of the lightest Higgs boson of the minimal supersymmetric model be larger than m(Z)?," Phys. Rev. Lett. **66**, 1815 (1991).

[26] S. Mizuta, D. Ng and M. Yamaguchi, "Phenomenological aspects of supersymmetric standard models without grand unification," Phys. Lett. B **300**, 96 (1993) [arXiv:hep-ph/9210241].

[27] K. A. Olive and M. Srednicki, "Cosmological limits on massive LSP ' s," Nucl. Phys. B **355**, 208 (1991).

[28] M. Kawasaki, T. Moroi and T. Yanagida, "Constraint on the Reheating Temperature from the Decay of the Polonyi Field," Phys. Lett. B **370**, 52 (1996) [arXiv:hep-ph/9509399].

[29] S. Mizuta and M. Yamaguchi, "Coannihilation Effects and Relic Abundance of Higgsino-Dominant LSPs," Phys. Lett. B **298**, 120 (1993) [arXiv:hep-ph/9208251].

[30] T. Moroi, M. Yamaguchi and T. Yanagida, "On the solution to the Polonyi problem with 0 (10-TeV) gravitino mass in supergravity," Phys. Lett. B **342**, 105 (1995) [arXiv:hep-ph/9409367].

[31] D. N. Spergel *et al.* [WMAP Collaboration], "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters," Astrophys. J. Suppl. **148**, 175 (2003) [arXiv:astro-ph/0302209].

[32] C. H. Chen, M. Drees and J. F. Gunion, "A Nonstandard string / SUSY scenario and its phenomenological implications," Phys. Rev. D **55**, 330 (1997) [hep-ph/9607421]; "Searching for invisible and almost invisible particles at e+ e- colliders," Phys. Rev. Lett. **76**, 2002 (1996) [hep-ph/9512230]; "Addendum/erratum for 'searching for invisible and almost invisible particles at e+ e- colliders' [hep-ph/9512230] and 'a nonstandard string/SUSY scenario and its phenomenological implications' [hep-ph/9607421]," hep-ph/9902309.

[33] M. Cirelli, N. Fornengo and A. Strumia, "Minimal dark matter," Nucl. Phys. B **753**, 178 (2006) [arXiv:hep-ph/0512090].

[34] K. Cheung, C. -W. Chiang and J. Song, "A Minimal supersymmetric scenario with only mu at the weak scale," JHEP **0604**, 047 (2006) [hep-ph/0512192].

[35] M. Cirelli and A. Strumia, "Minimal Dark Matter: Model and results," New J. Phys. **11**, 105005 (2009) [arXiv:0903.3381 [hep-ph]].

[36] M. R. Buckley, L. Randall and B. Shuve, "LHC Searches for Non-Chiral Weakly Charged Multiplets," JHEP **1105**, 097 (2011) [arXiv:0909.4549 [hep-ph]].

[37] L. J. Hall and Y. Nomura, "Spread Supersymmetry," arXiv:1111.4519 [hep-ph].

[38] J. Hisano, S. Matsumoto, M. M. Nojiri and O. Saito, "Direct detection of the Wino and Higgsino-like neutralino dark matters at one-loop level," Phys. Rev. D **71**, 015007 (2005) [hep-ph/0407168].

[39] L. Bergstrom and P. Ullio, "Full one loop calculation of neutralino annihilation into two photons," Nucl. Phys. B **504**, 27 (1997) [hep-ph/9706232].

[40] P. Ullio and L. Bergstrom, "Neutralino annihilation into a photon and a Z boson," Phys. Rev. D **57**, 1962 (1998) [hep-ph/9707333].

[41] A. A. Abdo *et al.* [Fermi-LAT Collaboration], "Constraints on Cosmological Dark Matter Annihilation from the Fermi-LAT Isotropic Diffuse Gamma-Ray Measurement," JCAP **1004**, 014 (2010) [arXiv:1002.4415 [astro-ph.CO]].